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FLIGHT INVESTIGATION OF A STALL-WARNING INDICATOR

FOR OPERATION UNDER ICING CONDITIONS

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SUMMARY

A preliminary investigation was made to determine
whether some characteristic of the boundary layer could be
used to provide satisfactory warning of the increase in
the stalling speed of a wing caused by ice formations on
the leading edge. The tests were conducted with a Lockheed
12A low-wing, twin-engine, all-metal transport airplane.
Wooden strips were used to simulate the ice formations and
total-pressure surveys were taken near the trailing edge
behind the wooden strips as the airplane was stalled.
Most of the stalls were made in level flight in the follow-
ing conditions: (1) cruising, 80-percent rated power;
(2) glide, power off, flaps retracted, landing gear up;
and (3) approach, power off, flaps fully deflected, land-
ing gear down. These flights were supplemented by a few
stalls, in only the cruising condition, in which the air-
plane was banked to produce normal accelerations ranging
from 1.2g to 1.6g.

The most promising characteristic of the flow near
the trailing edge that might be used as a warning of im-
pending stall was the decrease in total pressure at a
given level above the wing surface to a value slightly
above free-stream static pressure as the airplane speed
was reduced.

INTRODUCTION

The development of stall-warning indicators has long
been considered desirable because of the dangers associat-
ed with the unexpected stalling of an airplane and because
inherent warnings (such as tail buffeting) frequently are
not satisfactory. The requirements for an entirely satis-
factory stall-warning indicator are very severe. Adequate
and consistent warning should be provided with the airplane

in any condition of power or flap deflection, with the wing
loading changed because of variations in gross weight or
because of maneuvers, and with the local stalling speed of
any portion of the wing increased by ice formations on the
leading edge. Previous investigations by the NACA (reference
1) have produced a stall-warning device meeting all of the
listed requirements with the exception of providing warning
of increased local stalling speeds caused by ice formations.
The provision of warning for a wing on which ice has formed
presents a double problem because the stalling speed of the
wing as a unit is increased an unknown amount and also be-
cause the sequence of stalling of adjacent sections may be
altered.

The present test program for developing an indicator
to satisfy the foregoing requirements consists of two
parts. The first part is the determination of a basis
for stall warning at one section of the wing when that
section is made to stall prematurely by placing simulated
ice formations on the leading edge. Surveys were made on
the upper surface near the trailing edge to determine the
effect of the formations on the air flow over the wing
section as the airplane was stalled. The second part of
the test program consists of the extension of the surveys
to the rest of the wing in order that a series of indi-
cators located spanwise can be used to show the sequence
of section stalling. Preliminary tests covering the first
part of this program have been conducted by the NACA at
the Langley Memorial Aeronautical Laboratory and the re-
sults are reported herein.

APPARATUS

The airplane used for the investigation is a Lockheed
12A, twin-engine, low-wing monoplane shown in figure 1.
The wing details are shown in figure 2. The wing has a
span of 49.5 feet, split flaps lowering to a fully deflect-
ed position of 45°, and ailerons that droop 9.5° when the
flaps are fully extended.

Ice accretion on the wing was simulated by fastening
wooden strips with masking tape to the de-icer attachment
strip on the upper surface at about 50 percent semispan
from the plane of symmetry. (See fig. 2.) Two strips
were used - one of which was semicircular in cross section,
3 feet long, and 1/4 inch high and the other was triangular

in cross section, 2 feet long, and 1/2 inch high.

The rake used in making the pressure surveys at the trailing edge (see fig. 2) consisted of six tubes: one static-pressure tube and five total-pressure tubes. The total-pressure tubes were spaced 1/2 inch, and the lowest tube was 1/2 inch above the wing surface. The rake was located 12 inches forward of the trailing edge and behind the center of the wooden strip on the leading edge.

The static and total pressures measured with the rake were referred, respectively, to the free-stream static and total pressure measured with an airspeed head mounted about one chord length ahead of the wing tip. (See fig. 1.) A swiveling type of airspeed head that alines itself with the local flow was used to keep to a minimum the variation with speed of the static pressure measured by the airspeed head. The static-pressure orifices of the swiveling head were calibrated by means of a suspended trailing airspeed head. (See fig. 3.)

Several tufts were distributed over the wing to allow the observer to correlate the progress of stall with the measurement of pressures at the rake.

All pressures were recorded by an NACA recording manometer and correlated by means of an NACA timer. For a few of the tests, the normal acceleration at the center of gravity of the airplane was recorded by an NACA recording accelerometer.

PROCEDURE

Pressure records were taken as the airplane was gradually stalled in the following conditions: (1) cruising, 80-percent rated power; (2) glide, power off, flaps retracted, landing gear up; and (3) approach, power off, flaps fully deflected, landing gear down. The action of the tufts was continuously observed, and the approximate time at which more than one-half the tufts behind the wooden strip reversed their normal direction and then fluctuated forward and rearward was taken as the section stall. At that time, the switch controlling the manometer and timer was momentarily opened to identify the section stall condition on the pressure records.

Information concerning the effect of wing loading on

the pressures recorded at the rake was obtained during several stalls made in a cruising condition as the airplane was banked to increase the normal acceleration.

RESULTS AND DISCUSSION

The data obtained in these preliminary stall tests have been analyzed by referring total pressures at the rake to (1) free-stream total pressure, (2) static pressure at rake, (3) free-stream static pressure, and (4) static pressure from wing-tip swiveling head.

Total pressures at rake referred to free-stream total pressure.- With no simulated ice on the leading edge, the differences between the total pressures given by the three lowest rake tubes and the free-stream total pressure did not change sufficiently, as the airplane was stalled to serve as a warning. The rest of the rake total-pressure tubes, however, indicated an appreciable loss in total pressure as the section stalling speed was approached.

With the triangular strip mounted on the leading edge to simulate ice, however, the disturbance was so great that a loss in total pressure equivalent to free-stream dynamic pressure q at an airplane speed of 90 miles per hour, and equivalent to one-third free-stream dynamic pressure at an airplane speed of 160 miles per hour, was registered by a rake total-pressure tube 2.5 inches above the wing surface. Because of this large loss in total pressure, the use of the difference between rake total pressure and free-stream total pressure as a basis for stall warning was not considered feasible.

Total pressures at rake referred to static pressure at rake.- The local indicated velocities as determined from the difference between the rake total pressures and the rake static pressure were plotted against the difference between the indicated airplane speed and the speed corresponding to test-section stall. Figure 4 is representative of these plots and shows the indicated velocity at the rake total tube 1 inch above the wing surface for the condition with the half-round strip on the leading edge. The curves of this figure indicate a decrease in the local velocity at a rate that would provide a good basis for a stall-warning indicator but possess an undesirable feature in the high velocities attained in the ap-

proach condition. These high velocities were produced by
lowering the flaps, and their presence would require the
indicator setting to be a function of flap position. For
example, if the stall-warning device were set to operate
at a pressure corresponding to a local velocity of 45
miles per hour, reasonable warnings of 9.5 and 14 miles
per hour would be obtained for the glide and cruising con-
ditions, respectively, but practically no warning would
be provided for the approach condition. The indicator
would have to operate at a local velocity of about 67 miles
per hour to provide a satisfactory warning for the flap-
deflected condition. This undesirable feature of changes
in the indicator setting should be avoided, if possible,
although a mechanical connection between the flap and the
warning device to change the pressure at which the warning
device would operate is conceivable.

Total pressures at rake referred to free-stream static
pressure.- The possibility of including the flap-deflected
condition in a single indicator setting was presented when
the rake total pressures were referred to free-stream
static pressure and were plotted against the difference be-
tween the airplane speed and the speed for test-section
stall. Figure 5 shows this plot for the rake total-pressure
tube 1 inch above the wing surface for the two types of
strip used to simulate ice. This figure shows that, by
setting an indicator to operate when the difference between
the total pressure 1 inch above the wing surface and the
free-stream static pressure drops to a value of 0.3 inch
of water, warning (ranging from 7 to 14.5 mph) would be
provided for all the test conditions. The indicated air-
plane speeds for section stall in the cruising, glide, and
approach conditions were 86.5, 91.5, and 73.5 miles per
hour, respectively, with the half-round simulated ice
strip and 93.5, 107, and 79 miles per hour, respectively,
with the triangular strip.

The two curves for each airplane condition in figure
5(b) are the result of fluctuations in the total pressure
at the rake. These fluctuations could probably be greatly
reduced by introducing damping in the tubes connecting
the rake total-pressure tubes to the manometer; the warning
points in figure 5(b) have been selected, therefore, as
midway between the two curves for each airplane condition.

No curves are presented for the condition of no ice
on the wing because the portion of the wing surface shown
as the shaded area B in figure 2 always stalled first

with power off and sometimes stalled first with power on.
Surveys have not yet been made in area B, but the indi-
cator located in that region would probably be the first
to provide warning when no ice was present on the wings.

Figure 5 indicates that the loss in total pressure at
the trailing edge of an airfoil referred to free-stream
static pressure may serve as a basis for warning of ap-
proaching stall. In any practical application, however,
the total pressure cannot be referred to free-stream static
pressure. Furthermore, the magnitude of the ordinates in
figure 5 reveals that variations in the pressure used as
the reference source will have considerable effect upon
the degree of warning provided. For example, if a warning
indicator were set, as shown in figure 5(a), to provide a
10-mile-per-hour warning in the cruising condition, a
change in the reference static source equal to 5 percent
of the free-stream dynamic pressure at cruising stall would
change the amount of warning provided by 2 miles per hour.

Total pressures at rake referred to static pressure
from wing-tip swiveling head.- The effect of referring the
variation of total pressure at the rake to the static pres-
sure from the wing-tip swiveling head, which is a source
similar to that usually available in flight operations, is
shown in figure 6. The variations in the static pressure
from the swiveling head are shown in figure 3. The effect
of these variations on the degree of warning provided can
be determined by a direct comparison of figures 5 and 6,
inasmuch as the indicator setting has been taken to be the
same for all four figures.

Effect of wing loading.- The effect of wing loading
on the stall warning provided for the cruising condition,
with the half-round wooden strip on the leading edge, is
shown in figure 7. The normal acceleration varied by
±0.1g for any one stall because of the difficulties expe-
rienced in maintaining absolute control of all flight fac-
tors. The lower curve indicates the airplane speeds at
which stall warning would be given with increasing normal
acceleration provided that the warning indicator were set
to operate when the difference between the total pressure
1 inch above the wing surface and free-stream static pres-
sure dropped to 0.3 inch of water. The upper curve shows
the airplane speeds at which test-section stall was ob-
served for various values of normal acceleration. The de-
gree of warning can be seen to vary from 10 miles per hour
with normal wing loading to 16 miles per hour with the wing
loading corresponding to a normal acceleration of 1.5g.

Additional surveys.- Further investigations with the indicator located farther outboard than in the previous survey have confirmed the conclusion that, at points where flow conditions are essentially the same as those at the test section previously discussed, the loss in total pressure may serve as a basis for stall warning. Surveys at the trailing edge in the slipstream, however, indicate that the total pressure in the boundary layer is affected by power to such an extent that the variation of loss in total pressure cannot be used as a basis for stall warning in that region.

Limitations of total-pressure-loss type of indicator.- Some uncertainty may exist in a practical application using the variation in total pressure at the trailing edge of the wing referred to some source of constant pressure as a criterion for stall warning, inasmuch as the magnitude of this pressure variation may be so slight as to be influenced by a number of factors affecting the measurement of the reference pressure. One such factor is the location of the source of the reference pressure and another is the change in the physical characteristics of the instrument measuring the reference pressure. An extremely desirable feature of the stall-warning indicator of reference 1 is its ability to produce a pressure variation of large magnitude and, if this characteristic could, by further development, be incorporated in the total-pressure-loss type of indicator, the device would be more practicable to use than it is at the present time.

CONCLUSIONS

A preliminary flight investigation of the flow characteristics near the trailing edge of a wing, as the airplane was stalled with simulated ice on the leading edge, indicated the following conclusions:

1. The loss in total pressure at the trailing-edge rake, when referred to free-stream total pressure, was too greatly influenced by the ice formations to serve as a basis for a warning of the approach of the stall.

2. The change in local velocity at the trailing edge was sufficient and consistent enough to serve as stall warning, but the effect of the deflected flaps on the local velocity would require the indicator setting to be a function of flap position.

3. The difference between the total pressure at the trailing edge and either the free-stream static pressure or the static pressure of the swiveling airspeed head changed sufficiently to serve as a basis for stall warning in all the conditions tested. The variation of total-pressure loss, however, was too small to justify the practical application of this loss as a basis for stall-warning indication; further development would be desirable to produce a large pressure change at the warning device when the total pressure in the boundary layer reached the critical value.

4. For the cruising condition, the degree of section stall warning varied with increasing wing loading from 10 miles per hour with normal wing loading to 16 miles per hour with the wing loading corresponding to a normal acceleration of 1.5g produced by banking the airplane.

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    National Advisory Committee for Aeronautics,
        Langley Field, Va.

REFERENCE

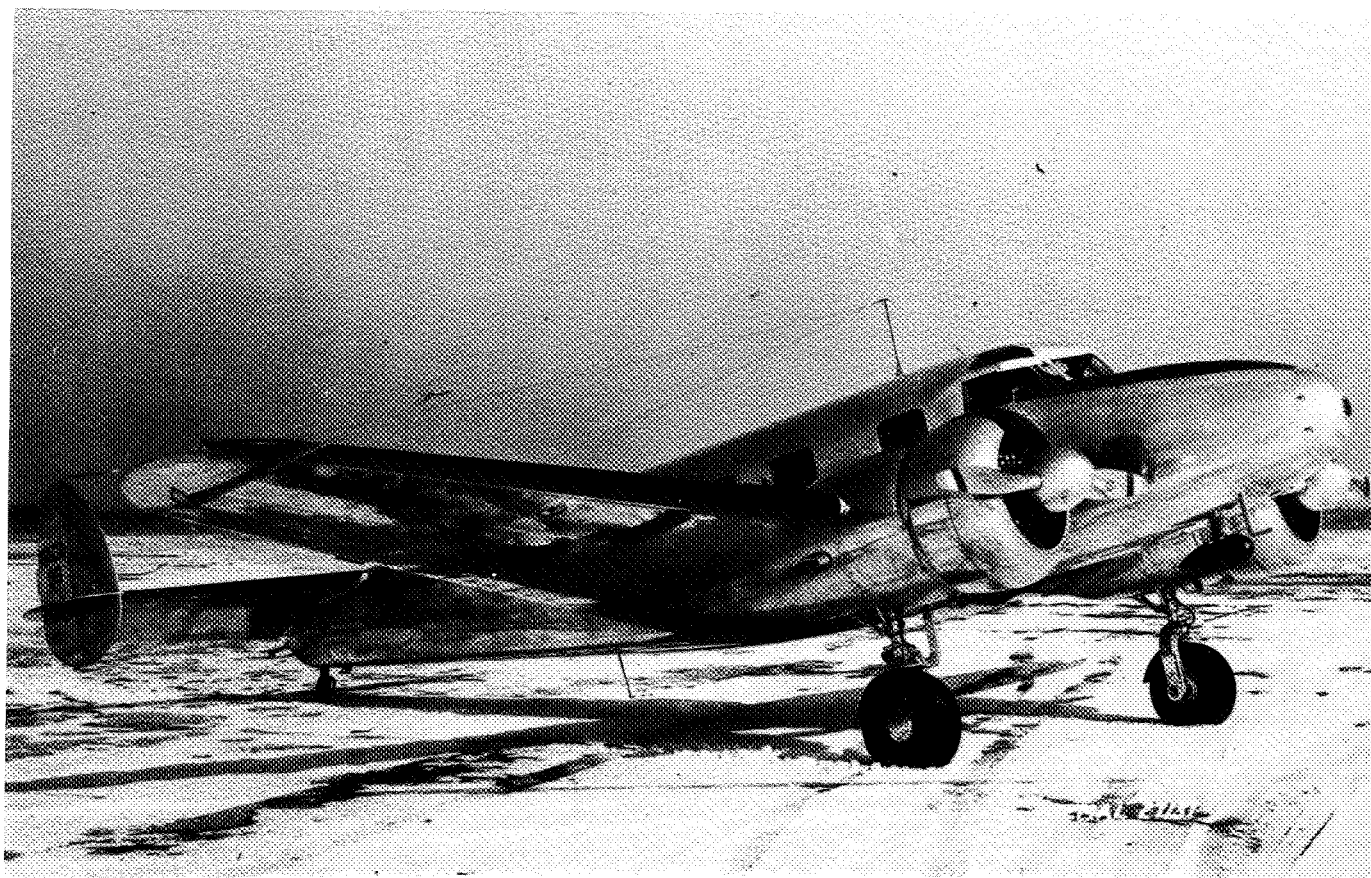1. Thompson, F. L.: N.A.C.A. Stall-Warning Indicator. T. N. No. 670, NACA, 1938.

Figure 1.- Lockheed 12A airplane used for stall-warning investigation. Swiveling air-speed head installed one chord length ahead of leading edge at right wing tip.
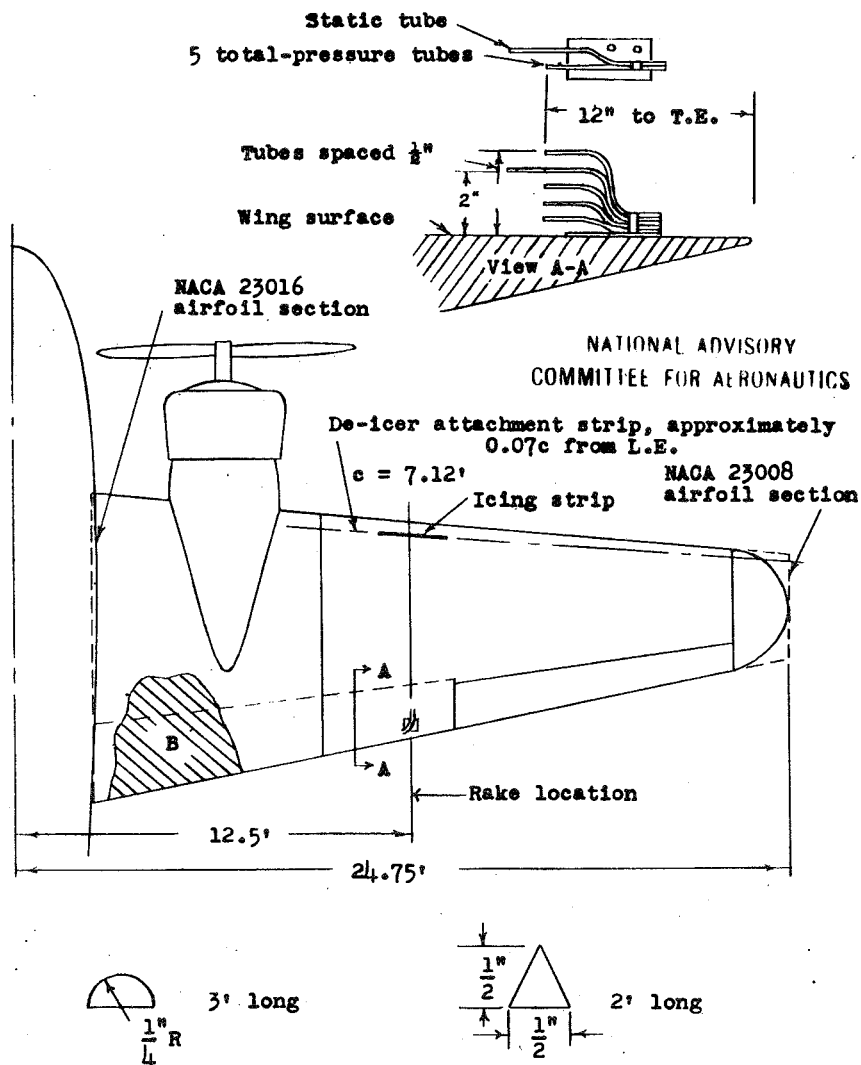
Fig. 1

Static tube

5 total-pressure tubes

12" to T.E.

Tubes spaced ½"

2"

Wing surface

View A-A

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NACA 23016
airfoil section

De-icer attachment strip, approximately
0.07c from L.E.

c = 7.12'

Icing strip

NACA 23008
airfoil section

A

B

A

Rake location

12.5'

24.75'

3' long

¼" R

½"

½"

2' long

Figure 2.- Location of survey rake and wooden simulated ice
strips during stall tests.

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Indicated airspeed, V_i , mph

180
160
140
120
100
80
60

Free-stream static pressure minus
swiveling-head static pressure
percent q   in. of water

.4
.2
0
-.2

—○— Cruising
—+— Glide
—×— Approach

10

0

2   4   6   8   10   12   14

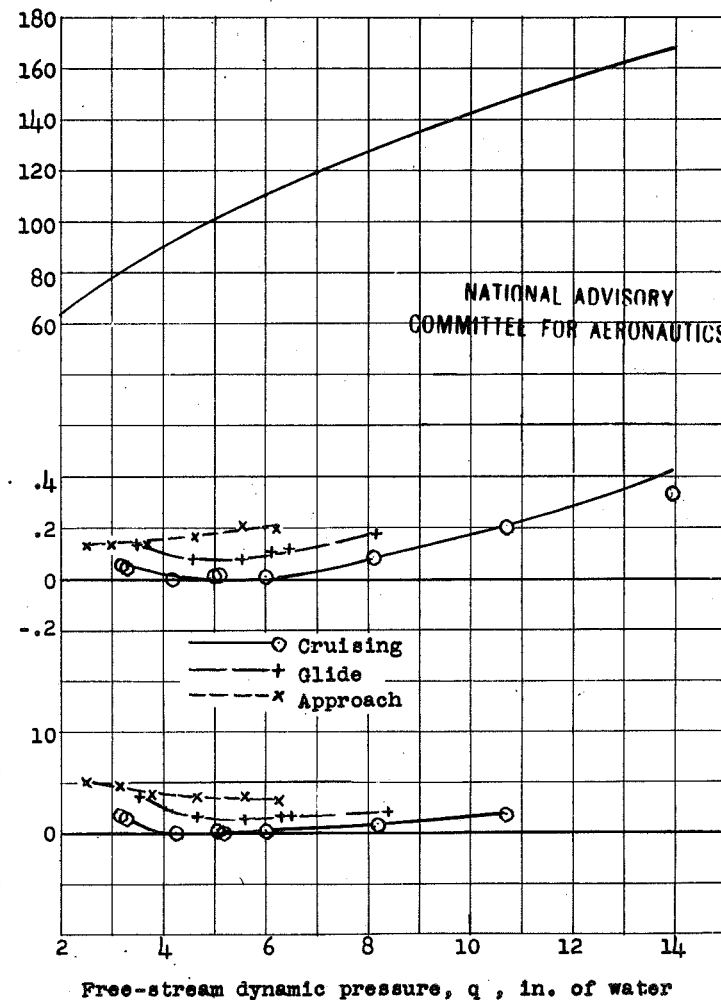Free-stream dynamic pressure, q , in. of water

Figure 3.- Calibration of the swiveling head mounted at the
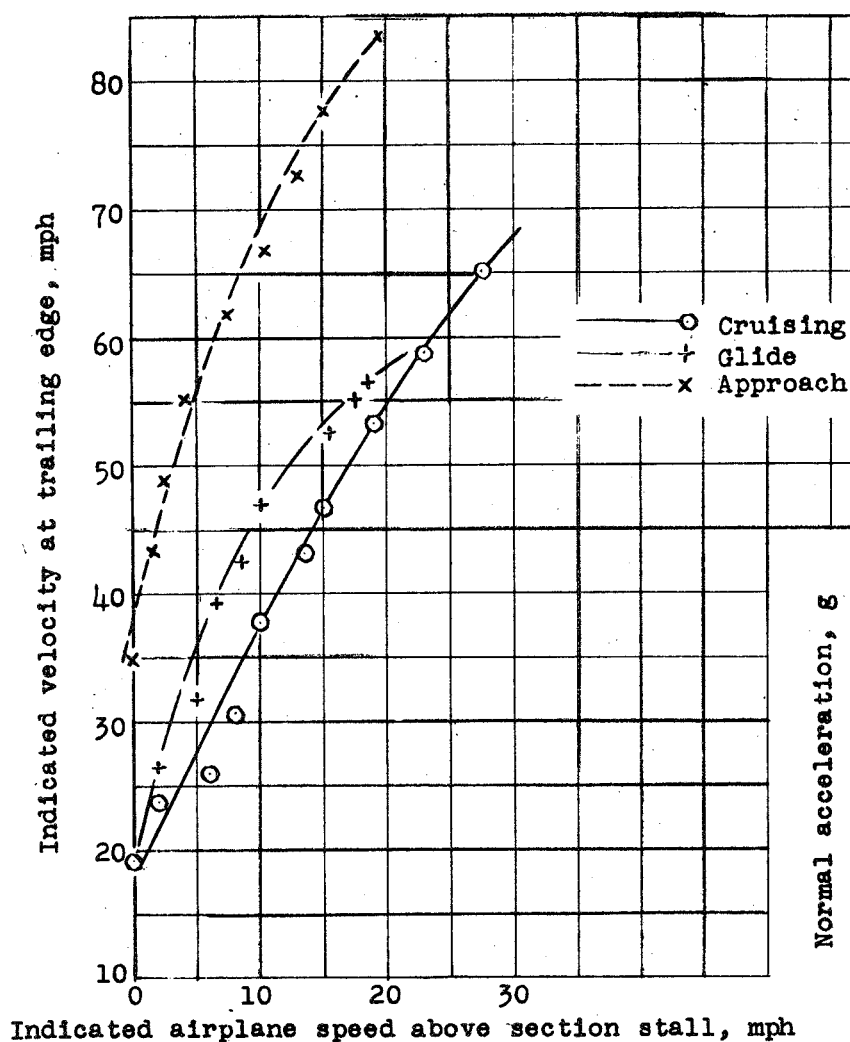Lockheed 12A wing tip. $V_i = 45\sqrt{q}$.

Figure 4.- Variation in indicated velocity
1 inch above wing surface and 12 inches
from trailing edge as obtained by use of
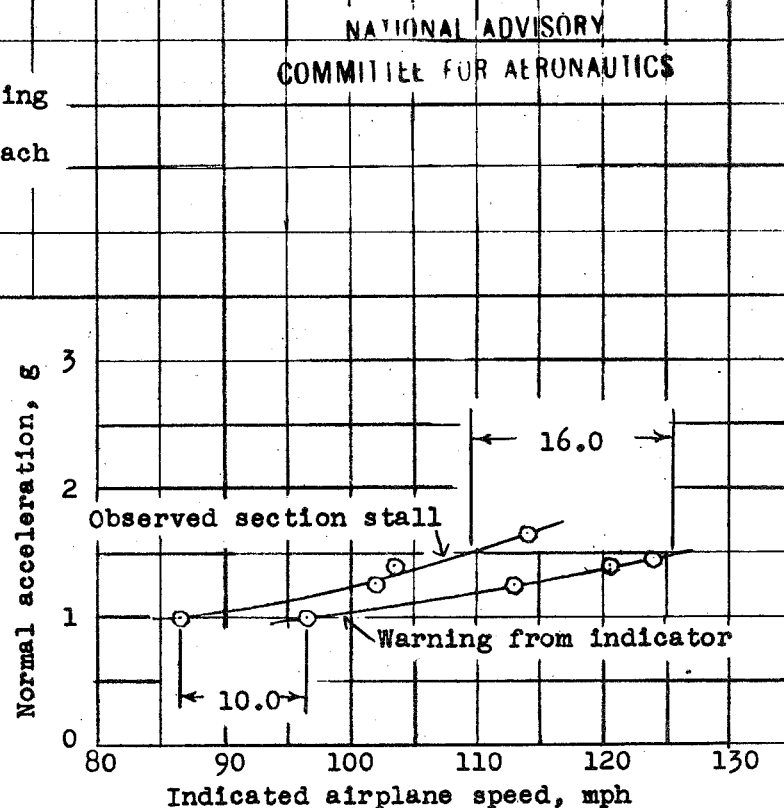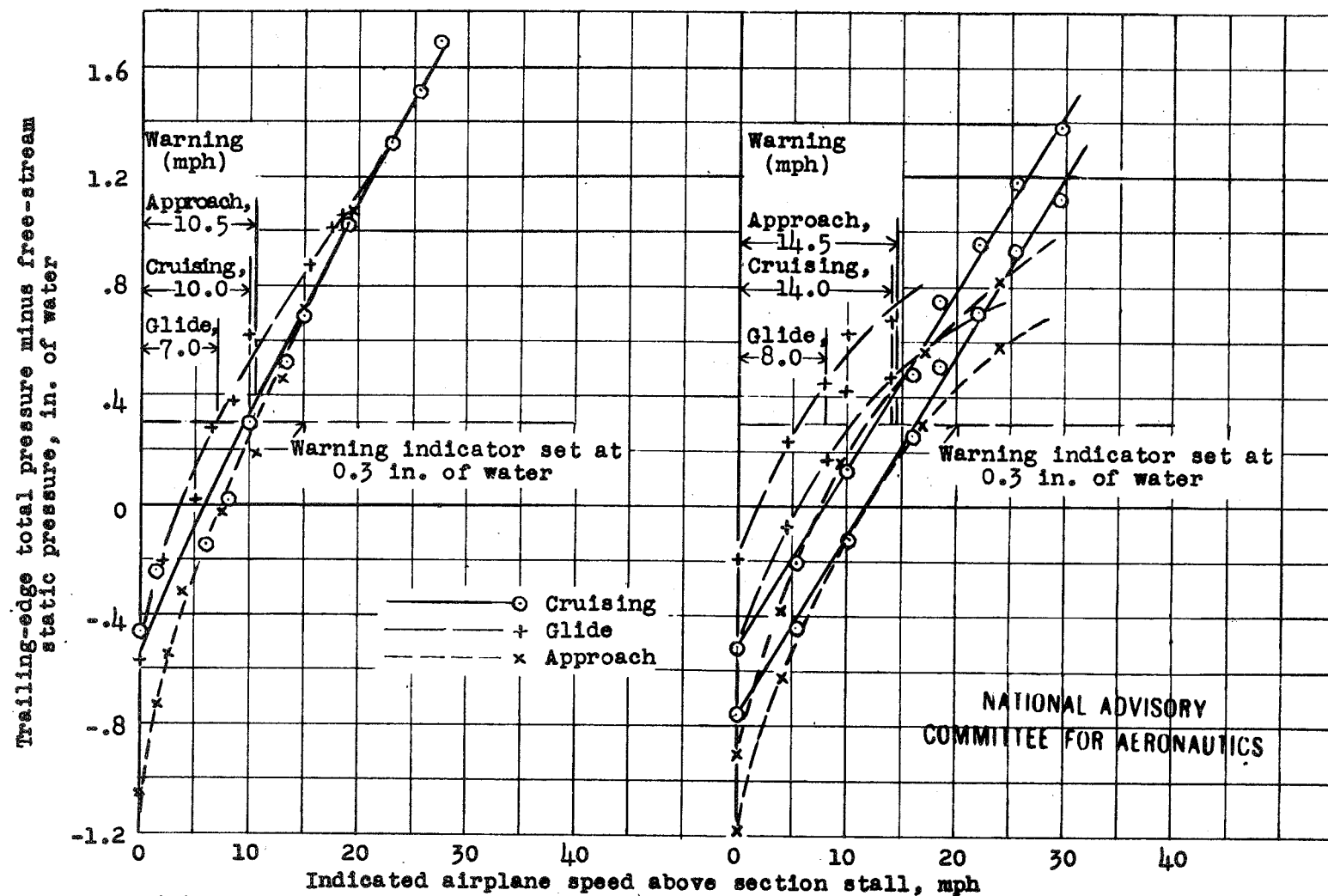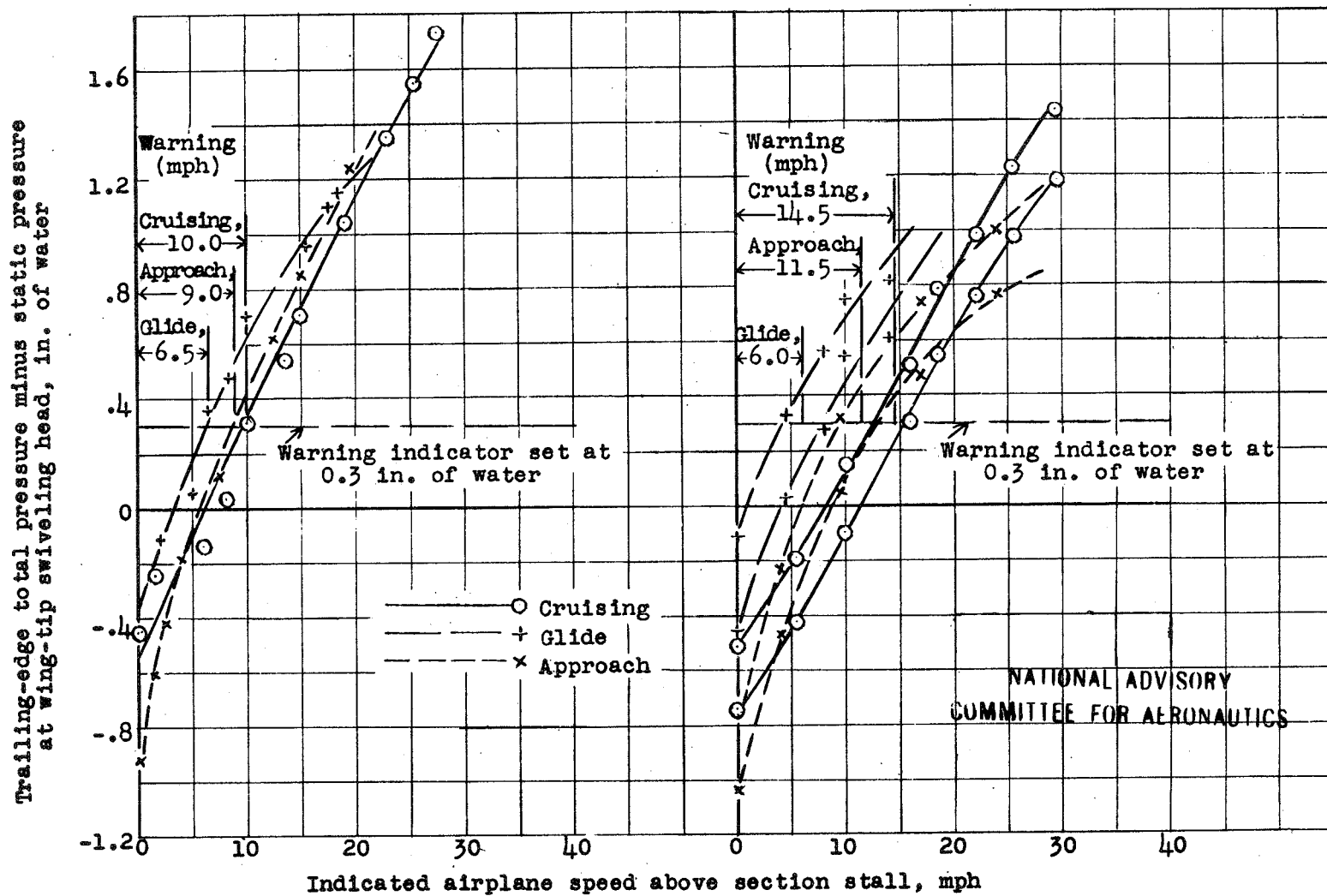half-round wooden strip.

Figure 7.- Effect of wing loading on
degree of warning in cruising condition.

(a) Half-round wooden strip.   (b) Triangular wooden strip.

Figure 5.- Variation in total pressure 1 inch above wing surface and 12 inches from trailing edge.

Fig. 5

Trailing-edge total pressure minus static pressure at wing-tip swiveling head, in. of water

Warning (mph)
Cruising, ←10.0→
Approach, ←9.0→
Glide, ←6.5→

Warning indicator set at 0.3 in. of water

○ Cruising
+ Glide
× Approach

Warning (mph)
Cruising, ←14.5→
Approach, ←11.5→
Glide, ←6.0→

Warning indicator set at 0.3 in. of water

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Indicated airplane speed above section stall, mph

(a) Half-round wooden strip.

(b) Triangular wooden strip.

Figure 6.- Variation in total pressure 1 inch above wing surface and 12 inches from trailing edge.

Fig. 6